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LIST OF ILLUSTRATIONS

I.   INTRODUCTION

This report presents the final summary with conclusions and recommendations of all work conducted during the entire gas velocity measuring device program. Work performed in this program was in accordance with the terms of Contract AF 04(611)-8157 for the Air Force Systems Command, Space Systems Division.

The objective of the program was to prove feasibility and deliver a "breadboard" test model of a rocket exhaust gas velocity measuring device which is independent of other gas parameters. The device is basically a magnetohydrodynamic generator in which the ionized rocket exhaust gas is used as the moving conductor within a magnetic field. The voltage generated normal to the gas flow is proportional to gas velocity in the field.

The velocity measuring device shown in Figure 1 consists of two Helmholtz magnetic coils having a uniform field between them and placed on an axis such that the rocket exhaust gas will pass between them in a direction perpendicular to the field. Probes on an axis $90°$ from the coil axis pick up the electromotive force generated.

II.   SUMMARY AND CONCLUSIONS

The gas velocity measuring device program appears to have demonstrated the feasibility of measuring a rocket exhaust velocity with a relatively simple device. However, additional testing and analysis is required to verify existing data before the feasibility can be definitely established. The device, comprising a magnetic field and voltage probes along with simple electrical equipment, is readily capable of either developmental test stand or portable field use with high temperature rocket exhaust gas.

FIGURE 1. GAS VELOCITY MEASURING DEVICE
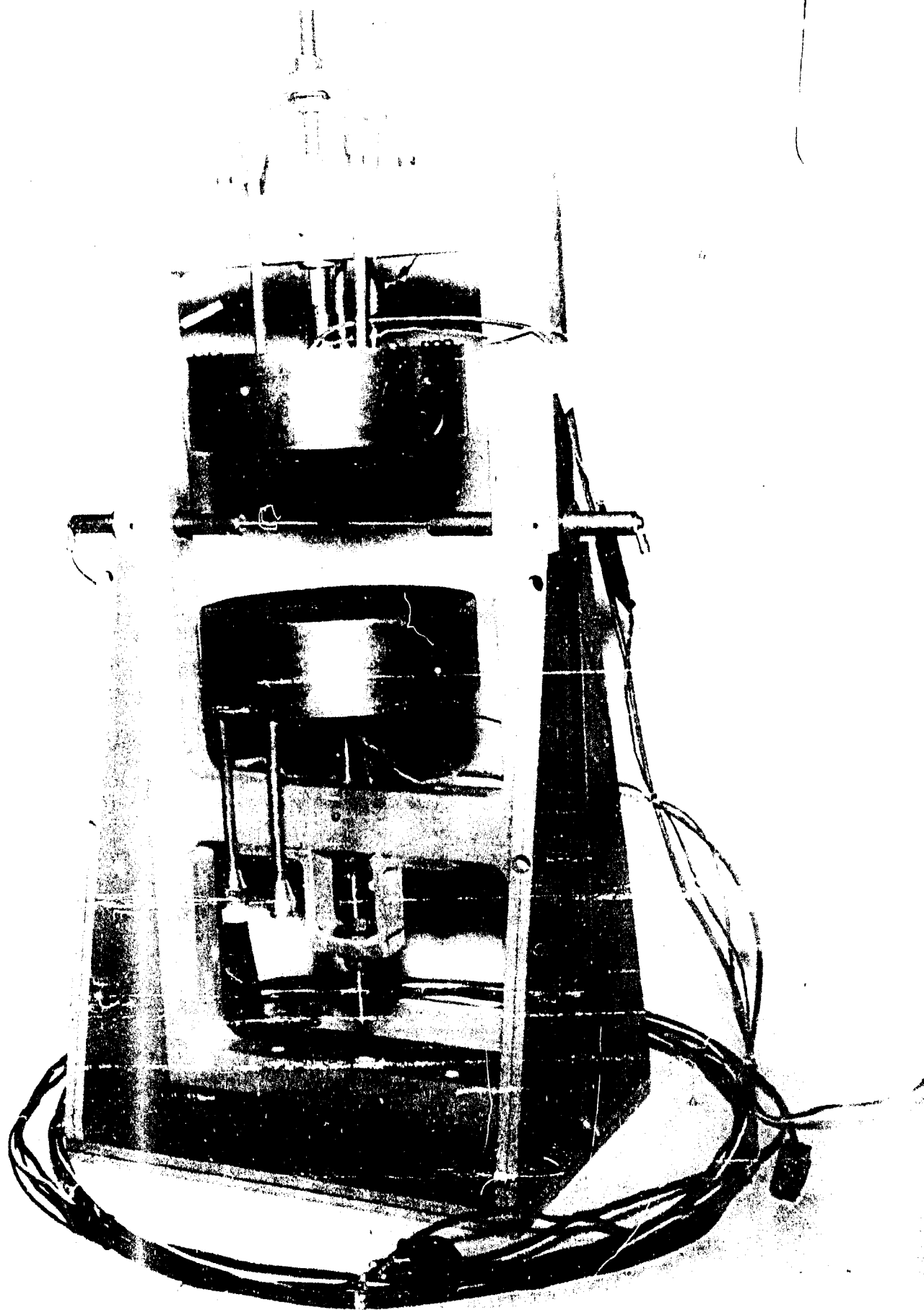
The feasibility of the gas velocity device has been demonstrated at Astrosystems on two rocket nozzle configurations. The first configuration was a separating nozzle in which operation at various chamber pressures provided a range of nozzle exhaust velocities. Test results obtained from the separating nozzle showed a consistent relationship between exhaust velocity at the plane of separation and measured probe voltage as shown in Figure 2. Since the exhaust gas must separate within the divergent section of the nozzle, the probes physically could not be located close to the gas separation plane. The probes, therefore, measured generated voltage in a plane downstream of the separation plane. The test results were not compared to theoretical gas velocity in the probe plane due to the complexity and inaccuracy of these calculations. This inaccuracy is caused by the gas flowing through a normal shock at the separation plane and several oblique shocks between these two planes.

The second nozzle configuration used for evaluating the velocity device was an ideally expanded nozzle. This nozzle permitted the voltage probes to be located close to the nozzle exit where the exhaust velocity could be calculated with reasonable accuracy. However, the range of test results is limited with this nozzle since the exhaust velocity is relatively constant for operation in the nonseparating regime.

In a significant number of runs, test results obtained with the ideally expanded nozzle showed actual probe voltages very close to theoretical voltages as shown in the following table:
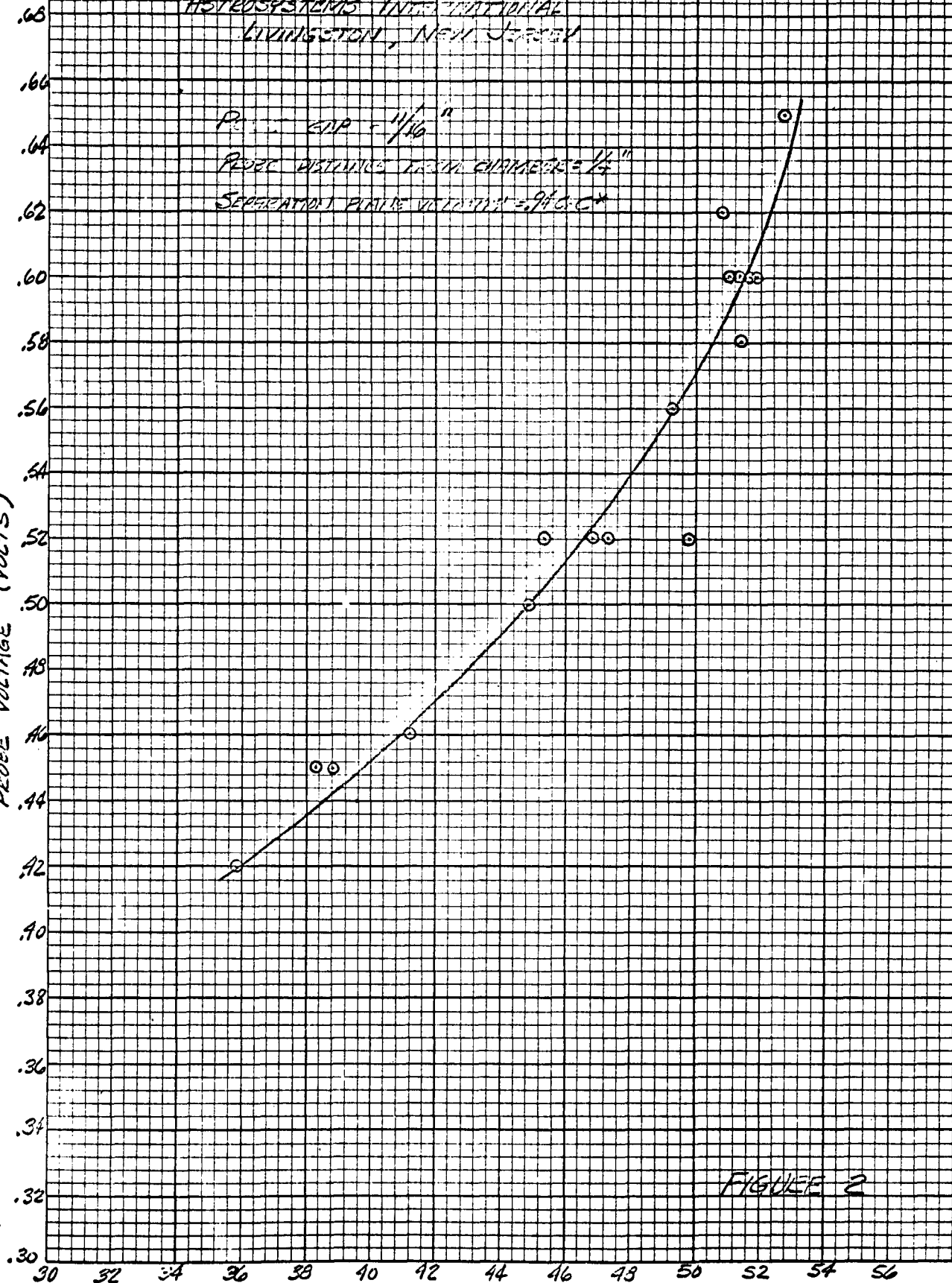
FIGURE 2

Table 1
Ideally Expanded Nozzle Test Results

Run No.	Exit Plane Velocity (ft/sec)	Probe Voltage	
		Theoretical volts	Actual (ave) volts
	$(.94\ c_F c*)$		
99	5290	.61	.60
102	5290	.578	.57
111	5240	.595	.60
112	5370	.580	.57
113	5450	.595	.60

During most of the test program, probe voltage was mea-
sured with a vacuum tube voltmeter having an input impedance
of 11 meg ohms. Near the end of testing, an electrometer
amplifier was made available to check the validity of test
results obtained by the 11 meg ohm device. The electrometer
amplifier, with adjustable input impedances ranging from
9,000 ohms to 90,000 meg ohms showed that 9 meg ohms had a
tendency to be marginal and that 90 meg ohms was a safer
level of input impedance. Therefore some of the voltage read-
ings from the vacuum tube voltmeter may have been slightly
less than that actually generated.

III. RECOMMENDATIONS

Three problem areas were encountered during the test pro-
gram of the gas velocity measuring device:

1. One area consisted of the various factors which detri-
mentally affected the probe voltage readings to the extent
of causing unusually high or low voltage readings or in some

cases, negative voltages.

For example, early in the program it was discovered that
the ionized gas produced a voltage potential which was an
order-of-magnitude larger than theoretical voltage. This
potential, which was found to produce up to 9.5 volts across
the probes without a magnetic field, was only introduced
into the probe circuit when a polarity was established and
maintained. A simple bucking circuit and an on-off magnetic
field was incorporated into the measuring device to elim-
inate the ionized gas potential.

It was also found that the probes must have clean points
to give reproducible results. While these factors have been
accounted for, some test runs conducted under apparently
identical conditions have produced differing results. For
example, test results of Runs 106 through 109 compared to
those of Runs 102 and 111 through 113 show a wide discrepancy
for seemingly identical test conditions. The reason for
these discrepancies is not understood due to the limited data
and number of runs available.

It is therefore recommended that more extensive testing
be conducted to analyze exterior factors which influence the
probe voltage.

2. The second problem area was that of obtaining an un-
steady voltage reading. Most voltage readings fluctuated ±.02
volts while some were estimated to be within ±.01 volts. It is
currently not known if 'the observed voltage fuctuations were
caused primarily by normal gas velocity fluctuations or by other
factors such as fluctuations in the ionized gas potential. It
would be possible to establish the source of these fluctuations
by performing tests with an alternating current magnetic field.
The theory of this type test is to superimpose an AC signal on
the probes and to filter out the DC potential from the ionized
gas. Although early tests in the program tried a 60 cycle AC
magnetic field, no probe voltage was recorded and the AC field
testing was discontinued.

It is recommended that additional testing be performed with
the AC magnetic field in effort to obtain a more accurate measure-
ment of gas velocity. Frequencies other than 60 cycles, perhaps
in the 2 to 20 cycle range, are suggested for these tests.

3. Although the scope of work in this program only considered testing on two nozzle configurations and one propellant combination, it would be most advantageous to demonstrate and prove the gas velocity measuring device with other exhaust nozzle area ratios and propellant combinations. Various exhaust nozzle area ratios would provide an assortment of exhaust gas velocities at ideally expanded conditions. The various propellant combinations would establish that the measuring device is independent of the exhaust gas composition and would also study the effects of various electrical conductivities of the exhaust gas.

These additional tests are recommended to establish the scope of application of the velocity measuring device.

IV. FEASIBILITY OF A PORTABLE FIELD MODEL

The gas velocity device is presently capable of field use. The measuring device as shown in Figure 1, Astrosystems' Part LO-00456, and the magnet control box are readily portable. A small portable vacuum tube voltmeter, such as the Hewlett-Packard 410B with 100 meg ohm input impedance, can be used to measure probe voltage. One man can easily carry these items.

A problem in portability may be the electric power source for the magnets. If 110 volt AC supply is available to field equipment, there is of course no portability problem. If a gasoline motor-generator type power supply must be used, then the degree of portability is limited by the generator.

The present measuring device is water cooled both to protect the magnets from the rocket exhaust and to absorb the heat generated by the electromagnets. The cooling required depends upon the duration of the firing. Firings up to 5 seconds would probably require no cooling and the device could be used "as is" with no cooling water. For intermediate duration firings, it would probably suffice to load the cooling coil with water to provide a heat sink. The long duration firings may necessitate access to tap water, or a radiator and water pump to be part of the velocity measuring device.

The gas velocity device even has the potential of being used in flight systems.

Making the gas velocity device flightweight, however, would require additional design studies. Since the electromagnets constitute a majority of the weight in the present device, the first area of study is that of reducing magnet size. The prototype model designed and built for this program was based on an arbitrarily selected magnet wire size and no consideration was paid to achieving minimum magnet weight for a given magnetic field and power input. This study would be necessary for a flight-weight unit. As discussed in Section III, Recommendations, the probe voltage reading accuracy should be improved. At the time this is accomplished the magnetic field could be reduced by greater than an order-of-magnitude without losing significant accuracy in the velocity measurements. The smaller magnetic field would be reflected almost directly in a weight reduction of the magnets.

A further weight reduction in the magnets may be possible if the magnets could be developed to focus the magnetic field between the probes. Additional study in this area would be required.

An estimated weight of a flight type velocity measuring device to accomplish the same task as LO-00456 could be 4.0 lbs, compared to the 31 lb weight of the present unit.

V.   TECHNICAL DISCUSSION

A total of 113 test firings were conducted during the program. Figure 3 shows the rocket engine test stand and Figure 4 shows the test console propellant tankage. Engine performance was generally between 5000 and 5500 ft/sec characteristic exhaust velocity (C*) for chamber pressures of 40 to 90 psia operating with gaseous oxygen and propane. Thrust was nominally 25 lbs. A Polaroid camera was used to photograph the engine test instrument panel during most of the tests. These photographs obtained instantaneous and more accurate test data than that recorded visually early in the program. The gas velocity device mounted for measuring velocity is shown in Figure 5.**

The two (2) Helmholtz electromagnetic field coils (toroidal) were wound with 1220 windings on each. The resultant magnetic field capability of these coils with the gap used for testing was theoretically and actually 242 gauss. The actual field was measured with a Dyna-Empire gaussmeter over a range of voltage inputs and plotted for voltage versus field in Figure 6. The magnetic field was altered slightly when the thrust chamber was immersed into the field. Curves under these conditions are also included in Figure 6.

The wire size used for the magnet is limited to 5 amp and its insulation is limited to a temperature of 220°F, corresponding to a current of 4.0 amp at 107 volts. Cooling coils around the magnet are provided to absorb the heat generated by the magnets as well as the heat from the rocket exhaust gases. Although thermocouples were imbedded within the center of each magnet, they were not used since one shorted during the winding operation. It was also felt that the temperature-conductivity relationship of the magnet wire provided a more accurate means of temperature monitoring.

** For a more detailed understanding of rocket engine principles of operation, conductivity of gases, and magnet principles, related literature is listed at the end of this report.

FIGURE 3. ROCKET ENGINE TEST STAND
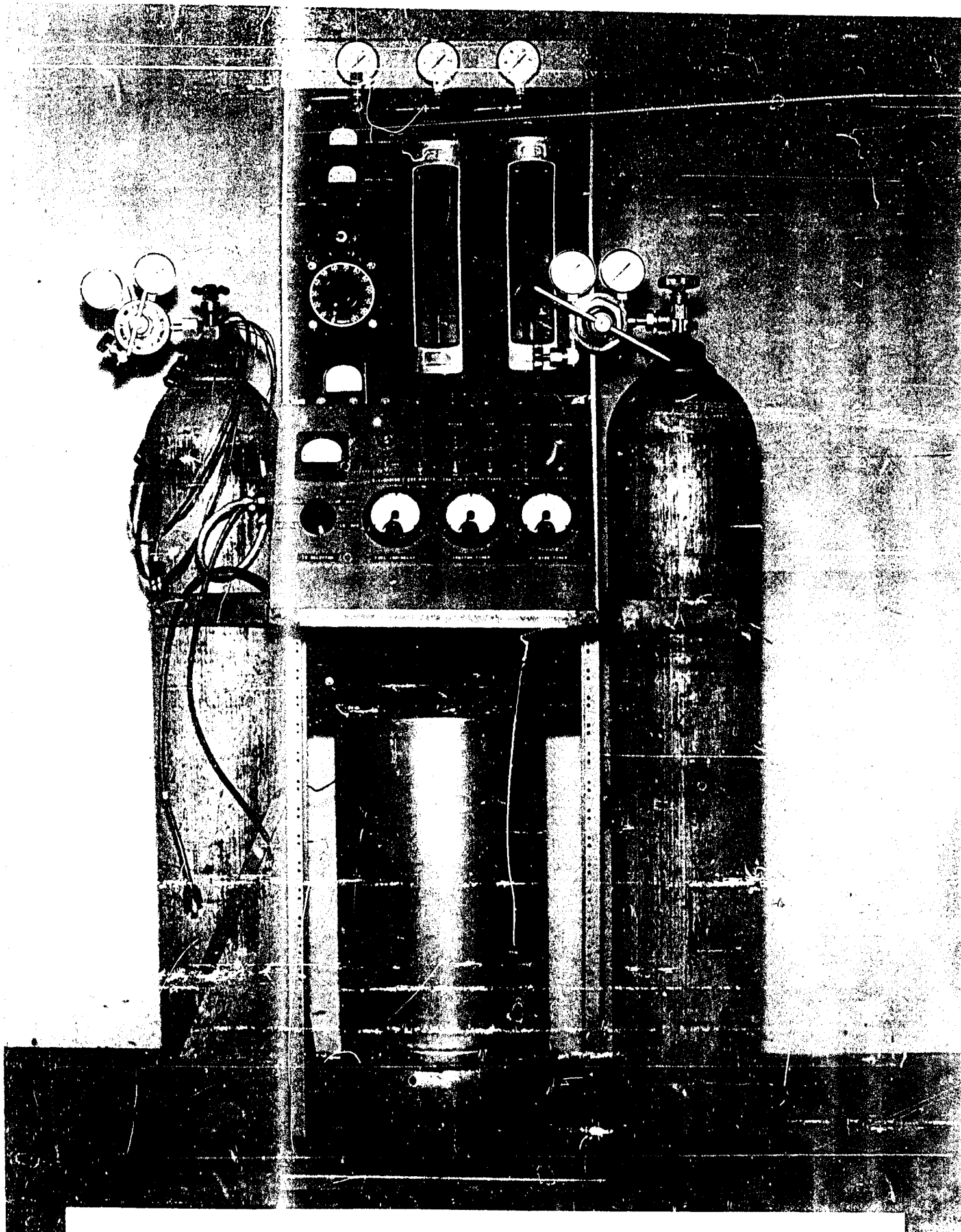
FIGURE 4. ROCKET ENGINE TEST CONSOLE AND PROPELLANT TANKAGE
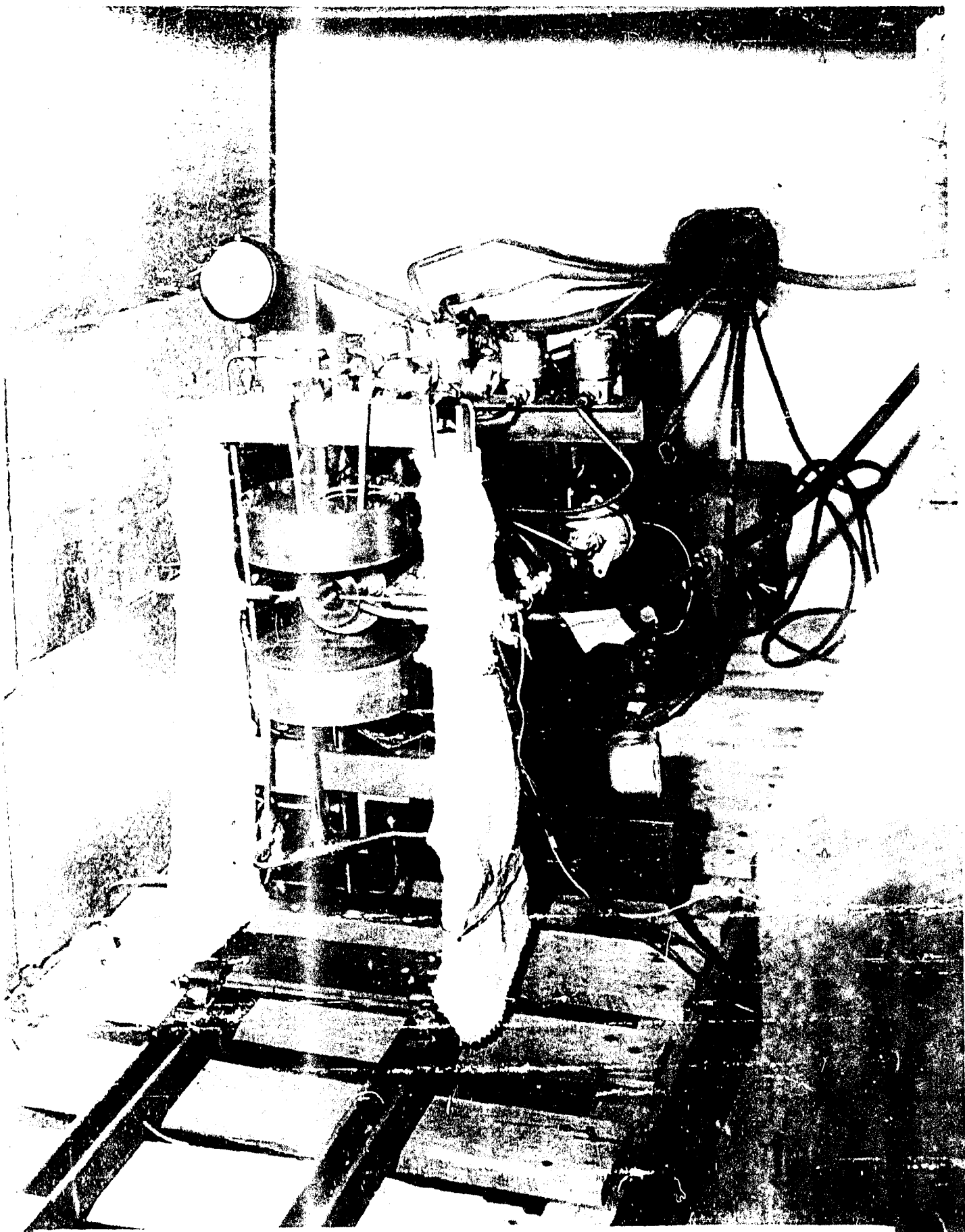
FIGURE 5. VELOCITY MEASURING DEVICE AND ENGINE TEST STAND

MAGNETIC FIELD vs MAGNET POWER

Astrosystems International, Inc.
West Caldwell, New Jersey

Measured Magnetic Field at Center of Helmholtz Coils
for a Magnet Gap of 4.36 in.
For (1) No Thrust Chamber in the Field
(2) Chamber with Separating Nozzle in the Field
(3) Chamber with Ideally Expanded Nozzle in the Field

FIELD WITHOUT THRUST CHAMBER

FIELD FOR SEPARATING NOZZLE

FIELD FOR IDEALLY EXPANDED NOZZLE

MAGNETIC FIELD (GAUSS)

MAGNET POWER (WATTS)

FIGURE 6

-13-

5/29/62

A silicon diode bridge rectifier circuit was incorporated
to supply 110 volts D.C. to the magnets. To avert damage to
the electromagnets when the field collapses as power is turn-
ed off, three neon lamps were placed in the circuit to dissi-
pate the voltage surge. The circuit schematic is shown in
SK 00513.

A.   Separating Nozzle Tests

The first nozzle configuration used for the velocity
measuring tests was an overexpanding, separating nozzle which
inherently was able to supply a range of exit plane velo-
cities as chamber pressure was varied. This nozzle was used
up to Run No. 95, as shown in Table II, Summary of Test Data,
for early development and reproducibility studies.

Although this nozzle was advantageous in that it provided
a variety of exit velocities, it did not provide velocities
which could be readily or accurately calculated in the same
plane in which they were being measured. The fact that the
exhaust gas separated well within the nozzle physically pro-
hibited the probes from being located at the gas exit plane
where the velocity can be calculated. The difficulty in
making probe plane velocity calculations is that the exhaust
gas passes through a normal shock wave at the separation plane
and several oblique shocks before reaching the plane in which
the probes are located.

Six tests were conducted on the rocket engine to ensure
satisfactory engine operation. Initial tests on the gas
velocity device indicated that a high impedance voltmeter was
necessary across the probes to obtain a realistic voltage
reading. Meters having impedances of 1000 ohms/volt and 20,000
ohms/volt were found to yield low signals. An 11 meg ohm (con-
stant) vacuum tube voltmeter indicated higher probe voltages
which were near anticipated values. This meter was used through
most of the testing.

TABLE II
PAGE 1

SUMMARY OF TEST RESULTS
GAS VELOCITY MEASURING DEVICE - LO-00456

No.	DATE	OX FLOW #/MIN	FUEL FLOW #/MIN	PcH PSIA	C* FT/SEC	CF	EXIT PLANE VELOCITY FT/SEC	MAGNET POWER WATTS	FIELD GAUSS	PROBE GAP IN.	PROBE DISTANCE IN.	MEASURED PROBE VOLTAGE	THEO. PROBE VOLTAGE	REMARKS
1	5/24/62	6.50	1.72	79.7	5290	—	—	—	—					ENGINE CHECK-OUT
2	5/24/62	6.57	2.20	84.7	5450	—	—	—	—					" "
3	5/24/62	6.5	1.85	74.7	6120	—	—	—	—					" "
4	5/24/62	6.57	1.95	94.7	6130	—	—	—	—					" "
5	5/25	6.0	1.87	77.7	5170	—	—	—	—					" "
6	5/25	5.93	1.87	74.7	5350	—	—	—	—					" "
7	5/29	NOT RECORDED		65				625	210	25/32	1/32	≈.05	—	1000 OHM/VOLT METER
8	5/29	5.70	2.25	84.7	5800	—	—	525	210	25/32	1/32	.05		" " " "
9	5/29	5.82	2.18	89.7	6110	1.000	6000	530	212	25/32	1/4	5.0	—	VACUUM TUBE VOLTMET.
10	5/29	5.92	2.05	89.7	6130	—	—	525	210	25/32	1/4	≈.05	—	1000 OHM/VOLT METER
11	5/29	5.92	2.05	89.7	6150	1.000	6100	505	210	25/32	1/4	6.6	—	VTVM
12	5/29	5.92	2.00	89.7	6170	1.000	6150	500	217	25/32	1/4	7.0 to 6.6	—	"
13	5/29	5.40	1.95	63.7	5100	.976	4680	675	230	25/32	1/4	6.2 to 4.8	—	"
14	6/1	6.03	1.99	84.7	5900	—	—	550	215	25/32	1/8	2.6 to 2.8	—	"
15	6/1	5.90	2.08	84.7	5770	—	—	535	217	25/32	1/2	5.4 to 4.2	—	
16	6/1	4.90	2.18	74.7	5750	—	—	535	216	25/32	1.0	.25	—	
17	6/1	NOT DETERMINED		86.7	—	—	—	650	232	7/8	1/4	9.5		
18	6/1	"	"	87	—	—	—	625	227	1.0	1/4	9.0		
19	6/1	5.92	2.07	84.7	5800	—	—	600	222	1/8	3/4	3.2	—	
20	6/1	5.92	2.03	77.7	5470	—	—	570	215	1/4	1/4	0	—	
21	6/1	5.92	2.07	77.7	5430	—	—	560	213	—	—	0		ONE PROBE ONLY AT GAP EQ. 7/16
22	6/4	6.02	2.02	77.7	5410	—	—	525	210	1/8	1/4	1.7	—	
23	6/4	6.00	2.07	77.7	5380	—	—	565	215	1.0	1/4	7.6		
24	6/4	5.92	2.12	77.7	5400	—	—	575	217	7/8	1/4	7.6 to 8.5	—	
25	6/4	5.92	2.09	77.7	5420	—	—	585	220	3/4	1/4	4.5	—	
26	6/6	5.92	1.75	77.7	5380	—	—	0	0	7/8	1/2	2.5		11 MEGOHM PARALLEL TO VTVM
27	6/16	5.92	1.75	78.7	5570	1.016	5340	510	210	7/8	1/4	.05	—	.5 to " "1110"
28	6/16	6.00	1.75	76.7	5370	—	—	208 A.C. FIELD		7/8	1/4	0 /.2 NOISE		VTVM & ENJO SCOPE A.C. TEST
29	6/19	5.92	2.30	78.7	5890	1.042	5170	510	210	7/8	1/4	.4 to .5	.775	VTVM WITH SINGLE BATTERY BUCKING V.
30	6/19	4.05	1.63	54.7	5250	PHOTO RESULTS		"	"	"	"	.4 to .2	—	" " PHOTO RUN
31	6/20	6.03	1.47	90.7	6550	1.001	6570	"	"	"	"	.35	1.05	.5 MFD CONDENSER IN PAR TO VTVM
32	6/20	6.20	2.03	82.7	5350	1.060	5330	"	"	"	"	.48	.82	" " "
33	6/20	6.33	1.87	80.7	5350	1.02	5150	550	212	"	"	.34	.535	" " "
34	6/20	4.05	1.07	43.7	5180	.7982	3890	550	212	"	"	.20	.48	" " "
35	6/21	6.50	2.22	84.7	5270	—	—	550	212	"	"	.1	—	" "
36	6/22	6.45	2.30	86.7	6100	1.05	—	510	210	"	"	0	—	" " "
37	6/22	6.57	3.30	86.7	5530	1.05	—	510	210	7/4	"	.62	—	" " "
38	6/22	6.45	2.25	84.7	5400	1.05	5330	650	235	5/4	"	.60	.83	" " "

TABLE II
PAGE 2

SUMMARY OF TEST RESULTS
GAS VELOCITY MEASURING DEVICE - LO-00456.

No.	DATE	OX. FLOW #/MIN	FUEL FLOW #/MIN	P_CH PSIA	C* FT/SEC	C_F	EXIT PLANE VELOCITY FT/SEC	MAGNET POWER WATTS	FIELD GAUSS	PROBE GAP IN.	PROBE DISTANCE IN.	MEASURED PROBE VOLTAGE	THEO. PROBE VOLTAGE	REMARKS
		ENGINE OPERATING DATA						MEASURING DEVICE DATA						
5	6/	6.55	1.10	77.7	5320	—	—	620	235	3/4	1/4	.20	—	.5 MFD CONDENSER BODY TO VTVM
9	6/	4.52	1.84	61.7	5600	—	—	0	0	"	"	−.14	—	" " "
41	6/	4.37	1.89	63.7	5260	—	—	610	225	"	"	−.34 +.34	—	" " "
42	6/	5.65	1.95	74.7	5380	—	—	0 540	0 210	"	"	0.7 1.2	—	" " "
43	6/	4.99	2.00	63.7	5490	—	—	540	0	"	"	.05 .14	—	" " "
44	6/	3.40	1.97	51.7	5550	—	—	540	206	"	"	.84 .74	—	" " "
45	6/25	5.80	2.12	74.7	5420	1.03	5250	0 540	0 210	"	"	−.65 −.1	.78 T	" "
46	6/25	5.94	1.98	74.7	5420	1.03	5250	540	210	"	"	.5±.1	.78 T	SINGLE BATTERY BUCKING VOLTAGE
47	6/27	6.10	2.00	72.7	5300	1.03	5130	540	210	"	"	.58→.60	.777 T	ADDED AMPL STAGE
48	6/27	6.10	2.05	80	5260	—	—	540	210	"	"	.5	—	.03 MFD ACROSS PROBE
49	6/27	5.90	1.95	71.7	5130	—	—	540	210	"	"	.55	—	SINGLE BATTERY & .03 MFD ACROSS VTVM
50	6/27	6.10	2.05	79.7	5300	—	—	550	212	"	"	.55±.1	—	" "
51	6/27	6.63	2.00	84.7	5330	—	—	535	205	"	"	.6	—	TWO BUCKING BATTERIES & .08 MFD ACROSS VTVM
52	6/27	6.35	1.85	83.7	5260	—	—	550	212	"	"	.6	—	" " "
53	6/29	6.33	2.16	83.7	5250	1.04	5270	540	210	INCREASE	"	.60±.02	.83 T	& .06 MFD ACROSS VTVM
54	6/29	5.83	2.16	84.7	5430	1.04	5320 T/K	560	215	1/2 CLOSE	"	.60±.02	.84 T	" " "
55	6/29	6.34	2.21	82.7	5270	1.03	5100 T/K	540	210	1/3	"	.55±.02	.78 T	" " "
56	6/29	6.72	2.10	85	5150	—	— T/K	540	210	1.0	"	0	—	" " "
57	6/29	6.71	2.05	86.7	5390	1.05	5300	540	210	7/3	"	.52±.02	.825 T	" " "
58	6/29	6.70	2.03	84.7	5130	1.04	5180 T/K	540	210	3/4	"	.56±.01	.795 T	" " "
59	6/29	4.96	1.92	67.7	5360	.975	4920 T/K	545	212	3/8	"	.48±.02	.695 T	" " "
60	6/29	3.18	1.13	40.7	5150	.774	3750 T/K	540	210	5/8	"	.45	.45 T	" " "
61	6/29	3.09	1.28	47.7	5330	.839	4120 T/K	670	210	5/8	"	.40±.02	.522 T	" " "
62	7/3	6.31	2.37	84.7	5250	—	— T/K	540	210	.75	"	.35±.1	—	BUCKING BATTERIES & PROBE CONDENSER
63	7/3	6.34	2.18	87.7	5290	—	— T/K	520	212	"	"	.4±.6	—	" "
64	7/3	6.85	2.27	88.2	5270	1.06	5250 T/K	520	212	.90	"	.4±.05	—	.03 MFD ACROSS CONDENSER
65	7/3	6.82	2.17	87.7	5300	1.05	5250 T/K	550	212	7/3	"	.50→.65	—	.03 MFD
66	7/3	6.52	2.00	85.7	5180	1.04	5150 T/K	540	212	7/12	"	.60±.01	—	" " "
67	7/3	6.47	1.93	82.7	5330	1.03	5150 T/K	550	212	"	"	.55±.02	—	C - ADD NEW BATTERIES & CONDENSER
68	7/3	6.92	1.97	86.7	5300	1.05	5230 T/K	540	210	"	5/8	.55±.02	—	" " "
69	7/3	6.68	1.83	84.7	5300	1.04	5180 T/K	540	210	"	1/3	.55±.02	—	" " "
70	7/3	6.85	1.94	84.7	5370	—	— T/K	540	210	"	5/8	.50±.02	—	" " "
71	7/3	6.85	1.65	82.7	5300	1.03	5130 T/K	540	210	"	1/2	.60±.01	—	" " "
72	7/3	6.88	1.51	82.7	5330	1.03	5330 T/K	540	210	"	3/8	.50±.02	—	" " "
73	7/3	6.74	1.56	81.7	5230	1.03	5080 T/K	540	210	"	3/4	.62±.02	—	" " "
74	7/3	4.12	1.22	49.7	5080	.81	3380 T/K	540	210	.635	1/4	.45±.02	—	" " "
75	7/6	4.60	1.67	59.7	5190	.92	4460 T/K	540	210	"	"	.50±.02	—	" " "
76	7/6	5.22	1.82	67.7	5240	.96	4730 T/K	540	210	"	"	.52±.01	—	" " "

TABLE II
PAGE 3

SUMMARY OF TEST RESULTS
GAS VELOCITY MEASURING DEVICE - LO-00456

	DATE	ENGINE OPERATING DATA						MEASURING DEVICE DATA						REMARKS
		OX. FLOW #/MIN	FUEL FLOW #/MIN	P_{CH} PSIA	C* FT/SEC	C_P	EXIT PLANE VELOCITY FT/SEC	MAGNET POWER WATTS	FIELD GAUSS	PROBE GAP IN.	PROBE DISTANCE IN.	MEASURED PROBE VOLTAGE	THEO. PROBE VOLTAGE	
72	7/8	5.82	1.94	74.7	5250	1.00	4930	540	210	.685	1/4	.56±.02	—	2-1.55 VOLT BATTERIES .02 MFD CONDENSER
73	7/8	6.33	1.90	80.7	5320	1.02	5100	540	210	"	"	.6	—	" " "
74	7/9	6.82	2.44	88.7	5230	1.06	5270	560	215	"	"	.65±.02	—	" " "
75	7/9	2.32	1.06	33.7	4730	.71	3160	550	212	"	"	.32±.04	—	" " "
76	7/9	3.75	1.44	44.7	4700	.83	3630	550	212	"	"	.45±.02	—	" " "
77	7/9	4.15	1.10	51.7	5080	.86	4120	540	210	"	"	.46±.02	—	" " "
78	7/9	CANCELLED COMBUSTION		59	—	—	—	540	210	"	"	.52±.01	—	" " "
79	7/9	5.13	1.42	65.7	5000	.960	4520	540	210	"	"	.52±.02	—	" " "
80	7/10	3.13	0.62	34.7	4980	.706	3290	540	210	"	"	.3±.05	—	" " "
81	7/10	3.00	0.65	34.7	5180	.71	3400	560	215	5/8	"	.35±.02	—	" " "
82	7/10	3.44	0.38	39.7	5010	.76	3530	560	215	.685	"	.42±.02	—	" " "
83	7/10	5.93	1.30	65.7	5240	.95	4450	540	210	"	"	.52±.01	—	" " "
84	7/10	6.03	1.64	74.7	5310	1.00	4730	540	210	"	"	.52±.02	—	" " "
85	7/10	CANCELLED COMBUSTION		70	—	—	—	540	210	.45	"	.45±.01	—	" " "
86	7/10	"	"	80 TO 40	—	—	—	540	210	"	"	.45±.01	—	PROBE 5/8 OFF CENTER
87	7/13	6.69	1.87	76.7	5220	—	—	540	210	.685	"	.45±.01	—	DOUBLE PETAL PROBE CIRCUIT
88	7/17	5.38	1.56	74.7	5470	—	—	540	210	"	"	.44±.05	—	" "
89	7/17	5.47	1.43	78.7	5170	—	—	540	210	"	"	.20 TO .76 COULD NOT READ	"	"
90	7/17	CANCELLED COMBUSTION		47	—	—	—	540	210	"	"	.62±.01	—	" "
96	7/17	4.47	1.27	53.7	5100	—	—	540	210	"	"	.30 —	—	.03 MFD CONDENSER "
97	7/17	4.38	1.30	52.7	5020	IDEALLY EXPANDED NOZZLE	—	540	180	"	"	SCATTERED	—	DOUBLE PETAL PUSHING CIRCUIT
98	7/17	4.81	1.08	55.7	4870	—	—	540	180	5/8	"	"	—	"
99	7/18	6.63	1.95	78.7	5060	1.114	5290	610	175	.685	"	.58 TO .62	.610	VTVM AND 2-1.55V BAT. & .01 MFD COND.
100	7/17	6.40	2.24	79.7	5030	1.114	5270	560	185	"	"	.375-.38	—	" " "
101	7/20	CANCELLED COMBUSTION		51	—	—	—	560	182	"	"	.77±.01	—	PROBE CENTER AND VTVM, ADJUSTED V
102	7/20	5.10	1.06	78.7	5070	1.11	5290	550	182	"	"	.57±.02	.575	" " 910 MC
103	7/20	5.78	2.30	74.7	5040	—	—	545	180	"	"	.3 TO .3	—	" " 900 MC
104	7/20	5.10	2.05	77.2	5100	—	—	535	178	"	"	.8 TO 1.3	SCATTER	" " "
105	7/20	6.33	2.02	79.7	5200	—	—	—	≈180	"	"	1.5	"	" " 900 MC
106	7/20	6.52	2.32	81.2	4980	1.12	5250	535	178	"	"	.35±.01	.56	" " 9,92,900, 900 MC
107	7/20	6.58	1.68	77.7	5120	1.11	5340	535	178	"	"	.85 TO .3	.58	" @ 994 900 MC
108	7/20	5.71	1.73	78.7	5080	1.114	5320	540	180	.750	"	.38±.01	.575	" " 90 MC
109	7/20	5.20	1.63	76.2	4980	1.10	5150	540	180	.750	.47	.40±.02	.557	" " "
110	7/20	6.10	1.63	77.2	5020	—	—	—	—	.85	.47	—	—	" " "
111	8/3	CANCELLED COMBUSTION		79.7	ASSUMED 5150	—	5120	560	185	.685	1/4	.60	.595	" " "
112	8/3	6.54	1.88	79.7	5150	1.11	5340	545	182	.685	1/4	.54 TO .58	.580	" " "
113	8/3	6.30	1.89	78.2	5210	1.11	5450	550	184	.685	1/4	.60±.01	.595	" " "

TABLE II NOTES

a)   +   denotes theoretical probe voltage is not for probe plane but rather for plane of gas separation within the nozzle. This value would be expected to be higher than measured value since effective velocity between separation and probe planes decreases.

b)   Propellants: Gaseous oxygen and gaseous propane

c)   Runs up to 97 use separating nozzle; runs 97 and above use ideally expanded nozzle with 1.68 area ratio.

d)   Distance between magnets = 4.36 inches.

e)   Tolerance on measured probe voltage is estimated according to fluctuations in VTVM reading.

f)   Theoretical probe voltage = Magnetic Field x Exhaust Gas Diameter x Gas Velocity at Exit Plane.

This equation is based on the basic physics equation for induced electromotive force:

$$e = Blv$$

where e = induced emf.
B = magnetic field
l = length of conductor
v = velocity of the conductor

Reference to this equation can be found typically in "University Physics" Sears and Zemansky, 1950 Page 570 or "Physics", Hausmann and Slack, 1939 Page 427.

g)   Exit plane velocity = $.94c_F C*$

h)   Gas ionization values are not considered since probe voltage is theoretically independent of the ionization level provided this level is above an acceptable value (approximately $10"$ ions/cc). Rocket combustion gases are well above this value.

Eighteen tests were performed in which probe voltages ranged from 0 to 9.5 volts depending upon the probe gap and the probe distance from the chamber nozzle. Anticipated probe voltages for some run conditions which produced 4.8 to 7.0 volts were an order of magnitude lower. The voltage difference was discovered to have been caused by the potential voltage of the ionized gas.[1] This potential was measured in the probe circuit once a polarity was established and maintained, even if no magnetic field existed.

To eliminate the ionized gas voltage potential, tests were performed initially with an alternating current magnetic field   (Run 28). The theory of these tests was to superimpose an A.C. signal on the probe pickup circuit and to filter out the D.C. potential caused by the ionized gas. The magnetic field was 60 cycle A.C. and probe voltage was fed to both a vacuum tube voltmeter and an oscilloscope. No voltage was recorded except 0.2 volt noise and the A.C. field testing was dropped. Although lower frequency A.C. tests were felt to have been worth while, previous D.C. results and program time considerations were deciding factors for concentrating on D.C. testing.

Various probe circuits were then devised to distinguish the D.C. ionized gas potential from the true signal resulting from the magnetic field. One approach tried was loading a condenser with the probe voltage and then switching the condenser to a voltmeter for measurement. This method yielded probe voltages from 0.2 to 0.6 volts which were order-of-magnitude with the theoretical voltages (Runs 31 through 45). Problems were encountered due to the condenser being sensitive to probe charge time, a short charge time not allowing the true voltage to build-up in the condenser, and a long charge time allowing the ionized gas voltage potential to also charge the condenser.

During these runs and all subsequent testing, the magnetic field was turned off frequently to establish a zero voltage reference thereby ensuring that the ionized gas potential

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[1] A. G. Gaydon, H. G. Wolfhard, "Flames", 2nd ed. 1960, p. 308.

was not influencing the voltage being measured.

During the next series of tests, an opposing voltage was placed in the probe circuit as shown below for use with a DC magentic field:
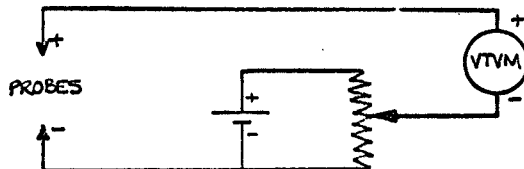
A 10K potentiometer and a 22 DC volt battery were used with the vacuum tube voltmeter. These tests (Run 29, 46 through 50) recorded voltages of 0.3 to 0.6 volts, substantiating the previous test results. Probe voltage readings had a significant fluctuation, which lead to the incorporation of a condenser and another bucking battery as follows:
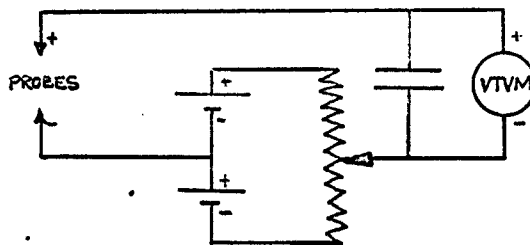
Runs 51 through 96 basically used this circuit. The condenser was used to minimize probe voltage fluctuations, giving voltage readings within 3 to 5 percent of their mean value. Condensers having .01 to .08 mfd were evaluated and .02 mfd produced the most desirable time constant. It was found that battery voltages as low as 1.35 volts were sufficient to prevent the ionized gas from establishing a circuit polarity. Other battery voltages tried were 22 volts and 9 volts, both of which caused over-sensitivity in the control of bucking voltage.

During the above runs, variations in the probes were evaluated. Flat-end probes were tested resulting in lower probe voltage readings. Electrical insulators were placed on all but the very tip of the probes, causing no noticeable voltage change. Also it was discovered that the probes must have clean tips to produce consistent voltage readings. Probe gaps and distances from the exit plane were varied. It was found that voltage was relatively insensitive to gap and distance within limits. For example, a 0.9 inch exhaust gas diameter produced nearly constant voltage for probe gaps between 5/8 and 7/8 inch and for distances from 1/8 to 3/4 from the end of the nozzle.

Results of tests having a constant gap and distance from the nozzle are plotted in Figure 2. Although the curve is plotted for separation plane velocity rather than probe plane velocity as discussed previously, it must be noted that the measured probe voltages were consistent relative to the separation plane velocity. Tests at other gaps and distances within the limits previously mentioned were also consistent with the data shown in Figure 2.

B.   Ideally Expanded Nozzle Tests

A second nozzle configuration was fabricated and tested. This nozzle was fully expanded so that the probes could be located close to the nozzle exit plane where velocity can be readily calculated.

This nozzle was first tested using the vacuum tube voltmeter circuit with the two bucking batteries and a condenser. Voltage was measured between 0.58 and 0.62 volts (Run 99). Theoretical voltage was calculated at 0.62 volts for the exit plane velocity of 5290 ft/sec. The test was repeated (Run 100) but voltage was measured at only .30 to .38 volts. This drop in voltage cannot presently be explained.

An electrometer amplifier was then made available for checking the required input impedance level. Adjustable impedances of 9×10^{-3} to 9×10^{4} megohms were applied to the circuit shown on the following page.
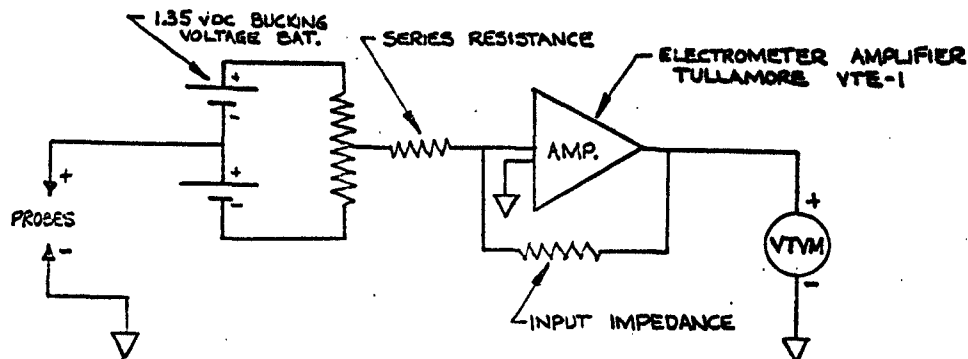
Levels below 9 megohms impedance resulted in low voltage readings and 90 megohms and above gave constant readings while 9 megohms was found marginal as it measured both constant and slightly lower values as shown by Runs 106 and 107. These runs as well as 108 and 109 gave probe voltages in the .3 to .4 volt range when theoretical was .55 to .58 volts. The discrepancy, although unexplainable is probably contributable to the same factor which influenced Run 100.

With no known change in the circuit or measuring device, the tests of Runs 106 through 109 were repeated and the results were probe voltages equal to theoretical, as presented in Table I, Section II, Run 111 measured .60 volts and theoretical was .595 volts for an exit velocity of 5420 ft/sec. Although the engine run data was not recorded because of a camera malfunction, the engine operation was identical to Run 112 and C* was determined from that run. Run 112 measured and theoretical voltages were .56 to .58 and .580 volts respectively. Exit plane velocity was 5370 ft/sec. Run 113 was identical to 111 in measured and theoretical probe voltages.

RELATED LITERATURE

Literature which is not directly applicable to this program but related so as to give a broader understanding of the subject includes:

1. "Rocket Propulsion Elements", G.P. Sutton, John Wiley and Sons, Inc., 1956.

2. "Fundamentals of Rocket Propulsion", R.E. Wiech, Jr. and R.F. Strauss, Reinhold Publishing Corporation, 1960.

3. "Gaseous Conductors", J.D. Cobine, Dover Publications, Inc., 1958.

4. "Revised Modern Physics", H.A. Wilson, 1931.

5. "Dynamics of Conducting Gases", Northwestern University Press, 1960.